Assessing the Validity and Reliability of Dichotomous Test Results Using Item Response Theory on a Group of First Year Engineering Students

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Abstract: Traditional measurement instruments employed to assess the performance of student’s studying on STEM (Science, Technology, Engineering and Mathematics) related programmes typically involve classification based on final scores. The validity and reliability of these instruments and test forms are important considerations when assessing whether a student understands content and if not, where and in what way they are struggling. The aim of this study is to examine, validate and analyse the test results of first-year engineering student’s at an Institute of Higher Learning in Ireland who took the Purdue Spatial Visualisation Test of Rotation (PSVT:R). Results obtained were analysed using the RASCH measurement model to see if it could be used to provide an alternative means of measuring student learning and to help identify those who may require extra assistance to overcome academic deficiencies, particularly where spatial skills have been linked to success. Findings may be used to inform on future improvements to teaching approaches and styles.

Keywords: Item Response Theory, Rasch measurement model, spatial visualisation, PSVT:R
Introduction

The primary aim of a measurement instrument is to quantify some phenomenon through the assignment of numbers to observations. Two key indicators of the quality of a measuring instrument are its validity and reliability (Kimberlin and Winterstein, 2008).

Multiple choice questions (MCQs) are a popular and widely used instrument for assessing student learning (Huntley et al., 2009; Pande et al., 2013). Different approaches to analysing MCQs exist (Ding and Beichner, 2009), with two popular frameworks being Classical Test Theory (CTT) and Item Response Theory (IRT) (Hambleton and Jones, 1993; Thorpe and Favia, 2012). Both attempt to align test-takers on a scale or latent trait continuum. The latent variable is typically a hypothetical construct such as ability, which is suggested to exist but cannot be measured by a single observable variable or item. Measurement of the latent variable is carried out indirectly through a test instrument consisting of multiple items.

CTT is a term which encompasses several types of psychometric tests. Most approaches assume that the observed score ($X$) obtained by the test-taker is made up of a true score ($T$) and a random error ($E$) giving $X = T + E$. IRT, on the other hand, takes what is known about the items e.g. difficulty, discrimination and the pattern of responses to the item and then makes an estimate of a person’s most likely level of the trait being measured e.g. ability. According to Fayers and Hayes (2005, p. 55), “IRT refers to a set of mathematical models that describe, in probabilistic terms, the relationship between a person’s response to a survey question/test item and his or her level of the ‘latent variable’ being measured by the scale”.

The Rasch measurement model was chosen as it is widely recognised as being a robust and objective measurement of latent traits (Hendriks et al., 2012). Its application can be found across many disciplines including, but not limited to, health, social sciences and education (Bonsaksen et al., 2013; Hudson and Treagust, 2013; Lerdal et al., 2014). A number of key assumptions underpin the Rasch model (Fischer, 1974).

1. **Unidimensionality**: All items are functionally dependent upon only one underlying continuum i.e. only one underlying factor accounts for a person’s response to a question within a scale.

2. **Monotonicity**: All item characteristic functions (ICF) are strictly monotonic in the latent trait. The ICF describes the probability of a predefined response as a function of the latent trait.

3. **Local stochastic independence**: Every person has a certain probability of giving a predefined response to each item and this probability is independent to the answers given to the preceding items.

4. **Sufficiency of a simple sum statistic**: The number of predefined responses is a sufficient statistic for the latent parameter.

5. **Dichotomy of the items**: For each item there are only two different responses such as yes/no, true/false, or agree/disagree.

Aim of Study

Research studies often present data obtained from test instruments without a rigorous critical reflection on what the data obtained from the instruments actually means despite numerous statistical tests existing to measure the validity and reliability of test instruments. The primary aim of this study is to examine how IRT can be used to determine the validity and reliability of data obtained. For this reason a popular test instrument (PSVT:R) used in engineering and other STEM related disciplines to evaluate the spatial ability of test-takers was chosen. While numerous studies have utilised spatial visualisation tests to measure the spatial ability of students’ (Sorby and Baartmans, 2000; Towle et al., 2005; Hamlin et al., 2006), less attention
has been given to examining the validity and reliability of the instrument measure with one notable exception being Maeda and Yoon (2011).

**Validity and Reliability**

Validity and reliability are key concepts in measurement. In order to be useful, measurement instruments should be both valid and reliable. According to Messick (1993) “Validity is an overall evaluative judgement of the degree to which empirical evidence and theoretical rationales support the adequacy and appropriateness of inferences and actions based on test scores”. Reliability is the extent to which the instrument consistently measures what it is intended to measure. While validity requires an instrument to be reliable, the reverse doesn’t hold as an instrument can be reliable without being valid (Kimberlin and Winterstein, 2008).

Formal definitions of validity vary so in an attempt to unify the theory of construct validity, in other words, how well the instrument does what it claims to do, Messick (1995) proposed a six faceted construct to measure the quality of the instrument: content, substantive, structural, generalisability, external and consequential. These facets have been used in numerous studies to validate the outputs produced by Rasch models (Wolfe and Smith, 2007; Beglar, 2010; Baghaei and Amrahi, 2011).

**Rasch Measurement Model**

The basis of the Rasch measurement model is that for each person taking a test there is an unobservable construct (or latent variable) being measured by a scale i.e. ability (\( \theta \)) and for each item on the test there is a parameter that measures the difficulty of an item response (\( \beta \)). Using these parameters Rasch (1960) proposed that the level of learning may be determined through the interaction \( \theta_i - \beta_j \) where \( \theta_i \) is the score of the \( i \)-th student (i.e. ability) and \( \beta_j \) is the score of the \( j \)-th item (i.e. difficulty). The probabilistic model for dichotomous data is given as:

\[
p(x_{ij} = 1|\theta_i, \beta_j) = \frac{e^{(\theta_i-\beta_j)}}{1 + e^{(\theta_i-\beta_j)}} = p_{ij}
\]

Equation (i) states how likely a person is to endorse a response category depends on how much of the trait they have and how difficult the item is. Data is collected and stored in a matrix form as depicted in Table 1. The table is made up of one row for each person (i.e. \( n \) rows) and one column for each item (i.e. \( j \) columns). Correct answers are indicated with ‘1’ and incorrect with ‘0’. The total score of student \( i \) for all items is given by the sum of each row i.e. \( \eta_i = \sum_{j=1}^{n} x_{ij} \). The score given by all students to item \( j \) is the sum of each column i.e. \( s_i = \sum_{i=1}^{n} x_{ij} \).

Due to the non-linear nature of the scores, a direct comparison between row and column totals is not possible. Rasch analysis converts the raw scores into linear units of measure called ‘logits’. The Rasch model uses a logit scale for both \( \theta_i \) and \( \beta_j \). The logit of \( p \) represents the log-odds of correctly answering an item. By taking the natural logarithm of both sides of equation (i), equation (ii) is obtained.

\[
\log\left( \frac{p}{1-p} \right) = \theta_i - \beta_j
\]

i.e.

\[
\log\left( \frac{\text{probability of success}}{\text{probability of failure}} \right) = \text{Ability} - \text{Difficulty}
\]

where

\[
p = p(x_{ij} = 1|\theta_i, \beta_j)
\]

Using logits makes it easier to make direct comparisons between student ability (\( \theta_i \)) and item difficulty (\( \beta_j \)). The proportion correct is simply an average of the column (item) or row (person) scores. Ability levels are obtained by taking the natural log of a ratio of the proportion correct to the proportion incorrect as illustrated by equation (v). Item difficulty is
obtained by taking the natural log of a ratio of the proportion incorrect responses to the proportion correct as illustrated by equation (vi).

\[
\theta_s = \ln\left(\frac{P_s}{1 - P_s}\right) = \ln\left(\frac{0.6}{1 - 0.6}\right) = 0.41 \quad \text{(v)}
\]

\[
\beta_5 = \ln\left(\frac{1 - \beta_s}{\beta_s}\right) = \ln\left(\frac{0.17}{1 - 0.17}\right) = 1.61 \quad \text{(vi)}
\]

The conceptualisation of the ability (latent) continuum as a ruler is illustrated in Figure 1. Person ability and item difficulty are converted into linear interval measures using a log-odds (logit) transformation. The mean item difficulty is assigned a logit value of 0 as the difference between person ability and item difficulty is not absolute but relative. The trait being measured may now be determined on a linear scale.

According to Harris (1989) item difficulty values can theoretically range from \(-\infty \leq \beta \leq +\infty\) but in reality generally range between \(-3 \leq \beta \leq +3\) with values in excess of \pm 3 rare. Similarly, person ability values can theoretically range from \(-\infty \leq \theta \leq +\infty\) but will generally lie in the range \(-3 \leq \theta \leq +3\).

**Methodology**

**Participants**

Test results from a sample of 236 students, who took the PSVT:R, form the basis of the analysis for this study. The test was administered to a cohort of first-year engineering (FYE) students at Dublin Institute of Technology at the start of their first semester (2014-2015).

**Instrument**

The PSVT:R is a widely accepted and respected instrument used in engineering education to measure the 3D visualisation ability of students. It was developed by Guay (1976) at Purdue University and consists of 30 items drawn in 2D isometric format. An example problem from the PSVT:R is shown in Figure 2. Here an object is shown on the top line which has been rotated by a given amount. Below this, a second object is shown which the test-taker must mentally rotate by the same amount and the correct view must then be chosen from the third line. Each item has only one correct answer. Students have 20 minutes to complete the test.
Statistical Analysis

All test data was analysed using Winsteps® Rasch Measurement software version 3.81.0 (Linacre, 2014) with results presented in Table 4. The sequence of steps outlined are based on a number of the construct validity facets proposed by Messick (1995), while person and item reliability are measured using the person separation index and Cronbach’s alpha coefficient (Cronbach, 1951). Unlike CTT, Rasch measurement does not require complete data sets so incomplete responses do not adversely affect the analysis.

Results

Summary Statistics

Table 2 provides summary statistics for both PERSON (test-takers) and ITEM (quiz question) measures. The value for MEASURE represents the estimated measure (for persons) or calibration (for items). In the Rasch measurement model INFIT is an inlier-pattern-sensitive fit statistic based on the chi-square (mean-square) statistic. It is more sensitive to unexpected behaviour affecting responses near to the measure level. OUTFIT is an outlier-sensitive fit statistic based on the chi-square statistic and is more sensitive to unexpected observations by persons on items that are relatively very easy or very hard for them (and vice-versa).

Table 2: Summary statistics from Winsteps® for both PERSON and ITEM measures.

<table>
<thead>
<tr>
<th>PERSON</th>
<th>ITEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>COUNT</td>
</tr>
<tr>
<td>MEAN</td>
<td>20.7</td>
</tr>
<tr>
<td>S.D.</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Fit statistics in the form of mean square (MNSQ) and standardised fit (ZSTD) are used to determine the goodness-of-fit of both PERSON and ITEM measures. MNSQ is a chi-square statistic used to compare expected results with those actually observed. Its value should be close to 1. A MNSQ value >1 indicates underfit (existence of embedded noise) while a value < 1 indicates overfit (results in inflated summary statistics). ZSTD reports the statistical significance (probability) of the chi-square statistics occurring by chance when the data fits the Rasch model i.e. it indicates how accurately or predictably data fits the model. The expected value for ZSTD is 0. A value <0 indicates that the data is too predictable while a >0 indicates a lack of predictability.

Item Difficulty

Item difficulty is estimated by the Rasch model. Table 3 provides a summary of the items on the PSVT:R in descending order of difficulty as determined by the Rasch model. Here ‘measure’ refers to the item’s measure calibration i.e. the higher the value the more difficult the test item. ‘Rotation’ describes the number of axis rotations required for an item and
whether the rotation is symmetrical (S) i.e. rotation confined to one axis or non-symmetrical (NS) i.e. multiple axis-rotations are required to arrive at the solution.

Table 3: PSVT:R item difficulty as determined by the Rasch model.

<table>
<thead>
<tr>
<th>Difficulty</th>
<th>Item #</th>
<th>Rotation</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q30</td>
<td>3-NS</td>
<td>2.74</td>
</tr>
<tr>
<td>2</td>
<td>Q29</td>
<td>3-NS</td>
<td>1.44</td>
</tr>
<tr>
<td>3</td>
<td>Q27</td>
<td>3-NS</td>
<td>1.25</td>
</tr>
<tr>
<td>4</td>
<td>Q26</td>
<td>3-NS</td>
<td>1.16</td>
</tr>
<tr>
<td>5</td>
<td>Q22</td>
<td>3-NS</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>Q28</td>
<td>2-S</td>
<td>0.96</td>
</tr>
<tr>
<td>7</td>
<td>Q13</td>
<td>2-S</td>
<td>0.56</td>
</tr>
<tr>
<td>8</td>
<td>Q25</td>
<td>2-S</td>
<td>0.56</td>
</tr>
<tr>
<td>9</td>
<td>Q12</td>
<td>3-NS</td>
<td>0.25</td>
</tr>
<tr>
<td>10</td>
<td>Q23</td>
<td>2-S</td>
<td>0.25</td>
</tr>
<tr>
<td>11</td>
<td>Q19</td>
<td>2-S</td>
<td>0.20</td>
</tr>
<tr>
<td>12</td>
<td>Q20</td>
<td>2-S</td>
<td>0.13</td>
</tr>
<tr>
<td>13</td>
<td>Q14</td>
<td>2-S</td>
<td>-0.03</td>
</tr>
<tr>
<td>14</td>
<td>Q21</td>
<td>2-S</td>
<td>-0.05</td>
</tr>
<tr>
<td>15</td>
<td>Q17</td>
<td>2-S</td>
<td>-0.08</td>
</tr>
</tbody>
</table>

Table 4: Summary of validity and reliability checks obtained from the Rasch model.

<table>
<thead>
<tr>
<th>Step</th>
<th>Psychometric Property</th>
<th>Statistical Approach and Criteria</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rating scale functioning: (substantive validity) Does the rating scale function consistently across items?</td>
<td>Average measures for each step category and threshold on each item should advance monotonically. z-values &lt;2.0 in OUTFIT mean square (MNSQ) values for step category calculations.</td>
<td>Item 13 did not meet criteria (z-value = 2.1) Item 14 did not meet criteria (z-value = 2.0)</td>
</tr>
<tr>
<td>2</td>
<td>Internal scale validity: (content validity) How well do the actual item responses match the expected responses from the Rasch model?</td>
<td>Item goodness-of-fit statistics: MNSQ &lt;1.3</td>
<td>All items met criterion</td>
</tr>
<tr>
<td>3</td>
<td>Internal scale validity: (structural validity) Is the scale unidimensional?</td>
<td>Principal component analysis: ≥50% of total variance explained by first component (spatial ability). Any additional component explains &lt;5% (or Eigenvalue &lt;2.0) of the remaining variance after removing the first component. No more than 5% (1 out of 20) of the residual correlations &gt;0.30</td>
<td>First component explained 70.0% of total variance. Second component explained 5.2% of total variance with an eigenvalue = 2.2 (2.0). Two out of 20 residual correlations &gt;0.3 (item 1 - item 2: r = 0.57, item 3 - item 4: r = 0.35)</td>
</tr>
<tr>
<td>4</td>
<td>Person response validity: (substantive validity) How well do the actual individual responses match the expected responses from the Rasch model?</td>
<td>Person goodness-of-fit statistics: INFIT MNSQ values &lt;1.5 and z-value ≤2.0. ≤5% of sample fails to demonstrate acceptable goodness-of-fit values.</td>
<td>1 out of 236 (&lt;&lt; 5%) respondents failed to demonstrate acceptable goodness-of-fit values</td>
</tr>
<tr>
<td>5</td>
<td>Person Separation Reliability: (reliability) Can the scale distinguish at least two distinct levels of sense of coherence in the sample tested?</td>
<td>Person Separation index: ≥2.0</td>
<td>2.07 (Real i.e. lower bound) 2.17 (Model i.e. upper bound)</td>
</tr>
<tr>
<td>6</td>
<td>Internal Consistency: (reliability) Are item responses consistent with each other?</td>
<td>Cronbach’s alpha coefficient: ≥0.8</td>
<td>0.87</td>
</tr>
</tbody>
</table>

a Linacre (2002)  
b Wright et al. (1994)  
c Linacre (2014)  
d Kottorp et al. (2003)  
e Fisher (1992)
Validity and Reliability

A summary of the validity (steps 1-4) and reliability (steps 5-6) checks are given in Table 4, the layout of which is adopted from Bonsaksen et al. (2013). The statistical approach and criterion for each of the psychometric properties investigated are outlined. The validity checks incorporate three (substantive, content and structural) of the six distinguishable aspects of unified validity put forward by Messick (1995). Two reliability coefficients are used i.e. the separation and reliability indices. The separation index represents how well the measurement instrument can distinguish between persons based on their ability location. Values between 2 and 3 for the separation index are considered to be very good levels for separation capacity (Fisher, 1992). The reliability index used in Rasch analysis is similar to Cronbach’s alpha (Bond and Fox, 2007).

Person Responses

Once the reliability and validity of the test instrument has been established the Rasch model can be used to examine the individual responses of the test-takers. In one example, Edwards and Alcock (2010) use the Rasch model to examine uncharacteristic responses.

For this study, Table 5 lists the 14 test-takers whose responses most misfit the Rasch model i.e. their responses differ from those estimated by the Rasch model. Fit statistics based on MNSQ and ZSTD values were used to identify test-takers who did not fit the Rasch model. The acceptable range of MNSQ is from 0.8 to 1.2 (Wright 1994) and ZSTD values are between -2 and 2 (Bond and Fox, 2007).

With reference to Table 5, consider the following:

- A large outfit-ZSTD value (>2) coupled with a high measure may indicate that a student has answered an ‘easy’ question incorrectly. In this study person 033 (score = 93%) answered item Q2 (measure = -1.03) incorrectly.
- A large outfit-ZSTD value (>2) coupled with a low measure may indicate that a student has answered a ‘tough’ question correctly and the remainder mostly incorrectly. In this study person 841 (score = 50%) answered item Q2 (difficulty = 2.74) correctly.

<table>
<thead>
<tr>
<th>#</th>
<th>Person</th>
<th>Total Score</th>
<th>Measure</th>
<th>OUTFIT</th>
<th>ZSTD</th>
<th>MNSQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>841</td>
<td>15</td>
<td>-0.03</td>
<td>5.2724</td>
<td>2.3986</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>659</td>
<td>16</td>
<td>0.13</td>
<td>3.1517</td>
<td>1.7253</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>536</td>
<td>16</td>
<td>0.13</td>
<td>3.1217</td>
<td>1.7157</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>973</td>
<td>27</td>
<td>2.53</td>
<td>2.5037</td>
<td>3.7344</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>677</td>
<td>17</td>
<td>0.28</td>
<td>2.3615</td>
<td>1.5263</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>017</td>
<td>25</td>
<td>1.86</td>
<td>2.2925</td>
<td>2.4689</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>033</td>
<td>28</td>
<td>3.03</td>
<td>2.2743</td>
<td>4.2725</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>596</td>
<td>24</td>
<td>1.6</td>
<td>2.1821</td>
<td>2.1409</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>525</td>
<td>18</td>
<td>0.45</td>
<td>2.0215</td>
<td>1.4671</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>923</td>
<td>22</td>
<td>1.16</td>
<td>-2.0095</td>
<td>0.464</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>668</td>
<td>20</td>
<td>0.79</td>
<td>-2.0394</td>
<td>0.554</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>212</td>
<td>17</td>
<td>0.28</td>
<td>-2.0794</td>
<td>0.6316</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>564</td>
<td>18</td>
<td>0.45</td>
<td>-2.1994</td>
<td>0.6082</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>921</td>
<td>17</td>
<td>0.28</td>
<td>-2.2194</td>
<td>0.6119</td>
<td></td>
</tr>
</tbody>
</table>

Discussion and Conclusions

Research has shown that results from the PSVT:R may be used as key indicators of success in STEM related disciplines (Humphreys, Lubinski, & Yao, 1993; Sorby, 2009; Wai, Lubinski, Benbow, & Steiger, 2010). For this study, the validity and reliability of the test instrument was reinforced by the results obtained and documented in Table 4. Overall, both person and item measures demonstrated acceptable goodness-of-fit and are positive indicators to the quality of the data and the test instrument.

While two items did not meet the criteria set out in Step 1 (see Table 4), they were only marginally outside the range and were not excluded in this instance. In terms of variance (see Table 6), the Rasch model explained 70.0% of the total variance in the dataset (i.e.
spatial ability). The secondary dimension explained 5.2%. As the first contrast is not much larger than the size of the eigenvalue expected by chance (<2.0) and although two out of 20 residual correlations were found to be >0.3 (see Table 4) there is strong enough evidence to support the existence of local independence of the items i.e. unidimensionality.

Table 6: Output from Winsteps® showing standardised residual variance values.

<table>
<thead>
<tr>
<th>Total raw variance in observations</th>
<th>--</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw variance explained by measures</td>
<td>--</td>
<td>12.9</td>
<td>30.0</td>
</tr>
<tr>
<td>Raw variance explained by persons</td>
<td>--</td>
<td>6.4</td>
<td>15.0</td>
</tr>
<tr>
<td>Raw variance explained by items</td>
<td>--</td>
<td>6.4</td>
<td>15.0</td>
</tr>
<tr>
<td>Unexplained variance (total)</td>
<td>--</td>
<td>30.0</td>
<td>70.0</td>
</tr>
<tr>
<td>Unexplained variance in 1st contrast</td>
<td>--</td>
<td>2.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Unexplained variance in 2nd contrast</td>
<td>--</td>
<td>1.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Unexplained variance in 3rd contrast</td>
<td>--</td>
<td>1.7</td>
<td>3.9</td>
</tr>
<tr>
<td>Unexplained variance in 4th contrast</td>
<td>--</td>
<td>1.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Unexplained variance in 5th contrast</td>
<td>--</td>
<td>1.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

A high positive residual correlation (r) can indicate local item dependency whereas a large negative correlation indicates the opposite of local dependence. The residual correlation obtained from this study was r = 0.4 which may be considered low dependency. With a person-separation index of 2.07 combined with a reliability of 0.87 (see Table 4) it can be concluded that the test instrument used was able to distinguish between two categories of test-takers. A value of 2.07 indicates that the test instrument detected two statistically distinct groups of participants for the trait being investigated i.e. in this case, test-takers with high and low spatial ability. Cronbach’s alpha reports the approximate test reliability based on raw scores and with a value of 0.87 obtained from this study is above the acceptable value of 0.8.

The Rasch model has a role to play in both engineering education for assessing students through MCQs, surveys etc., and in engineering education research as a tool for examining the validity and reliability of measures obtained from various test instruments, not just the PSVT:R which was used in this study. As the example provided in this paper illustrates, the RASCH model may be used to provide an alternative means for measuring student learning ability and can help identify those who may require targeted intervention. Findings from this and similar studies may be used to inform on future improvements to teaching approaches and styles.

References


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